

# Results on axion physics from the CAST experiment at CERN

Christos Eleftheriadis

*Nuclear Physics and Elementary Particles Section  
Aristotle University of Thessaloniki  
for the CAST Collaboration \**

## Abstract

Axions are expected to be produced in the sun via the Primakoff process. They may be detected through the inverse process in the laboratory, under the influence of a strong magnetic field, giving rise to X-rays of energies in the range of a few keV. Such an Axion detector is the CERN Axion Solar Telescope (CAST), collecting data since 2003. Results have been published, pushing the axion-photon coupling  $g_{a\gamma}$  below the  $10^{-10} \text{ GeV}^{-1}$  limit at 95% CL, for axion masses less than 0.02 eV. This limit is nearly an order of magnitude lower than previous experimental limits and surpassed for the first time limits set from astrophysical arguments based on the energy-loss concept. The experiment is currently exploring axion masses in the range of  $0.02 \text{ eV} < m_a < 1.1 \text{ eV}$ . In the next run, currently under preparation, the axion mass explored will be extended up to the limit of 1.1 eV, testing for the first time the region of theoretical axion models with the axion helioscope method.

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\* S. Andriamonje<sup>2</sup>, S. Aune<sup>2</sup>, K. Barth<sup>1</sup>, A. Belov<sup>12</sup>, B. Beltrán<sup>7</sup>, H. Bräuninger<sup>6</sup>, J. Carmona<sup>7</sup>, S. Cebrián<sup>7</sup>, J. I. Collar<sup>8</sup>, T. Dafni<sup>4,2</sup>, M. Davenport<sup>1</sup>, L. Di Lella<sup>1</sup>, C. Eleftheriadis<sup>9</sup>, J. Englhauser<sup>6</sup>, G. Fanourakis<sup>10</sup>, E. Ferrer-Ribas<sup>2</sup>, H. Fischer<sup>11</sup>, J. Franz<sup>11</sup>, P. Friedrich<sup>6</sup>, T. Geralis<sup>10</sup>, I. Giomataris<sup>2</sup>, S. Gninenko<sup>12</sup>, H. Gómez<sup>7</sup>, M. Hasinoff<sup>13</sup>, F. H. Heinsius<sup>11</sup>, D. H. H. Hoffmann<sup>4,5</sup>, I. G. Irastorza<sup>2,7</sup>, J. Jacoby<sup>14</sup>, K. Jakovčić<sup>16</sup>, D. Kang<sup>11</sup>, K. Königsman<sup>11</sup>, R. Kotthaus<sup>15</sup>, M. Krčmar<sup>16</sup>, K. Kousouris<sup>10</sup>, M. Kuster<sup>4,6</sup>, B. Lakić<sup>16</sup>, C. Lasseur<sup>1</sup>, A. Liolios<sup>9</sup>, A. Ljubičić<sup>16</sup>, G. Lutz<sup>15</sup>, G. Luzón<sup>7</sup>, D. Miller<sup>8</sup>, A. Morales<sup>7</sup>, J. Morales<sup>7</sup>, A. Nordt<sup>4,6</sup>, A. Ortiz<sup>7</sup>, T. Papaevangelou<sup>1</sup>, A. Placci<sup>1</sup>, G. Raffelt<sup>15</sup>, H. Riege<sup>1</sup>, A. Rodríguez<sup>7</sup>, J. Ruz<sup>7</sup>, I. Savvidis<sup>9</sup>, Y. Semertzidis<sup>17</sup>, P. Serpico<sup>15</sup>, L. Stewart<sup>1</sup>, J. Villar<sup>7</sup>, J. Vogel<sup>11</sup>, L. Walckiers<sup>1</sup>, K. Zioutas<sup>17,1</sup>

1. European Organization for Nuclear Research (CERN), Genève, Switzerland
2. DAPNIA, Centre d'Études Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France
3. Department of Physics, Queen's University, Kingston, Ontario

## 1 Introduction

CP violating terms in quantum chromodynamics give rise to a non-vanishing neutron electric dipole moment, EDM. However, experimental efforts have put tight upper limits,  $d_n < 2.9 \cdot 10^{-26} \text{ e} \cdot \text{cm}$  <sup>1)</sup>, which is orders of magnitude more strict than the prediction of theory. The question of CP conservation in QCD, which is known as the strong CP problem (SCPP), can be answered through the existence of at least one massless quark, a hypothesis which is experimentally excluded, since all quarks have mass <sup>2)</sup>. Up to now, the most convincing solution to the SCPP was given by Peccei and Quinn <sup>3)</sup>, <sup>4)</sup> through the introduction of a new global U(1) symmetry, which is spontaneously broken at an energy scale  $f_a$ . Through this process, the CP violation in strong interactions is dynamically suppressed. According to the Nambu-Goldstone theorem, the break down of the symmetry generates a Nambu-Goldstone boson, a spinless particle, the axion. Axions are expected to be much alike pions. If they exist, they should interact very weakly, being also very light particles. Depending on their density and mass, they may constitute a candidate for the cold dark matter in the universe. Axion parameters, namely their mass and PQ symmetry breaking scale are related through the following expression

$$m_a = 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a} \quad (1)$$

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4. Technische Universität Darmstadt, IKP, Darmstadt, Germany
  5. Gesellschaft für Schwerionenforschung, GSI Darmstadt, Germany
  6. Max-Planck-Institut für extraterrestrische Physik, Garching, Germany
  7. Instituto de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain
  8. Enrico Fermi Institute and KICP, University of Chicago, Chicago, IL, USA
  9. Aristotle University of Thessaloniki, Thessaloniki, Greece
  10. National Center for Scientific Research “Demokritos”, Athens, Greece
  11. Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
  12. Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia
  13. Department of Physics and Astronomy, University of British Columbia, Department of Physics, Vancouver, Canada
  14. Johann Wolfgang Goethe-Universität, Institut für Angewandte Physik, Frankfurt am Main, Germany
  15. Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany
  16. Rudjer Bošković Institute, Zagreb, Croatia
  17. Physics Department, University of Patras, Patras, Greece

where  $f_a$  is the axion decay constant or breaking scale of the Peccei–Quinn symmetry and  $m_a$  is the axion mass.

Axions are also expected to be copiously produced in stellar cores through their coupling to plasma photons, with energies in the range of keV. Since their coupling is small, they escape nearly freely, carrying away amounts of energy from the star. This dissipation mechanism, if present, increases the rate at which the stars consume their fuel, in order to counterbalance the axion energy loss. For supernovae environments the axion energy may reach even 160 MeV. They constitute again an energy dissipation mechanism. In general, in all stellar objects, from white dwarfs to horizontal branch stars, energy dissipation by axions add a new energy loss channel which can affect the evolution timescale of these objects and, therefore, their apparent number density on the sky <sup>5)</sup>.

Searches for axions are intense nowadays, including not only the idea of the helioscope <sup>6, 7)</sup> presently used by CAST <sup>8, 9, 10)</sup>, but also Bragg scattering <sup>11, 12, 13)</sup>, cavity searches <sup>14)</sup>, the PVLAS experiment method <sup>15, 16, 17)</sup>, the "through the wall" <sup>16, 18, 19)</sup> or even "through the sun" method <sup>20)</sup>. Astrophysical and cosmological arguments are involved in order to shed light on their characteristic parameters <sup>5, 21)</sup>. Solar mysteries may also be explained in terms of axions <sup>22)</sup>. Axions with earth origin have been also discussed <sup>23)</sup>.

CAST is designed to measure axions, produced by the Primakoff effect in the stellar plasma of the central area of our sun. Other potential sources of axions may also become of interest in the future.

## 2 Axion production in the sun

The dominant mechanism in axion production is the conversion of a plasma photon into an axion, in the field of a charged particle. Other contributions, such as the "electro-Primakoff" effect, are not important, because all charged particles in the sun are not relativistic and, therefore, are not able to provide high B fields. Photons of energy E in a stellar plasma may be transformed into axions through the Primakoff effect at a rate given by

$$\Gamma_{\gamma \rightarrow \alpha} = \frac{g_{\alpha\gamma}^2 T \kappa_s^2}{32\pi} \left[ \left( 1 + \frac{\kappa_s^2}{4E^2} \right) \ln \left( 1 + \frac{4E^2}{\kappa_s^2} \right) - 1 \right] \quad (2)$$

In this relation, natural units have been used. T is temperature and  $\kappa$  is the screening scale in the Debye-Huckel approximation <sup>24)</sup>.

$$\kappa_s^2 = \frac{4\pi\alpha}{T} \left( n_e + \sum_{nuclei} Z_j^2 n_j \right) \quad (3)$$

A discussion on the solar axion flux on earth can be found in reference 24, where also the dependence of flux on two different solar models is given.

### 3 The CAST experiment

The experiment uses a recycled superconducting test magnet from LHC, with a length of 9.26 meters and can reach a magnetic field of 9 T at 13 kA. The magnet has two pipes, as all LHC magnets, with a cross sectional area of 14.5 cm<sup>2</sup> each. It is mounted on a moving structure and it may track the sun for nearly 3 hours a day, half of the time during morning and half in the evening. This limitation comes from the fact that it is not possible to increase the elevation angle of the superconducting magnet more than  $\pm 8^\circ$ . Coverage of azimuthal angle is 100°. On both ends of the magnet, on all four apertures X-ray detectors are mounted. Namely, on the front side, looking for X-rays during sunset, there is a conventional Time Projection Chamber (TPC) detector<sup>25)</sup> with an area covering both holes. On the other side, one aperture is covered by a position sensitive gaseous micromegas detector (MM)<sup>26)</sup>, whereas on the second aperture an X-ray telescope<sup>27) 28)</sup> is mounted. Solar axions with an energy spectrum peaking at 4.2 keV, are transformed into photons via time reversed Primakoff effect, under the influence of the transverse magnetic field of 9 T. The conversion probability is given by

$$P_{a \rightarrow \gamma} = \left( \frac{g_{a\gamma} B}{q} \right)^2 \sin^2 \left( \frac{qL}{2} \right) \quad (4)$$

$q = m_a^2/2E$  being the momentum difference between axion and photon. These photons are expected to be recorded by the three detectors as signal over background, only when the sun and the magnet are aligned. The rest of the time the detectors are measuring pure background. All detectors are able to measure background also simultaneously with the signal, since they are position sensitive and their effective area is bigger than the aperture of the magnet. As a matter of fact, whatever is recorded outside the area of the detector covering the magnet's aperture, is pure background even at the time of the alignment of the magnet to the sun. This is especially true for CCD, since the area of the focal point of the x-ray telescope is very small, less than 10 mm<sup>2</sup>. It is an evident advantage to measure background and signal at the same time, leading to reduced systematics. A detailed description of the experiment, as well as of the detectors and the x-ray telescope can be found in references 24, 25, 26, 27, 28, 29, 30.

### 4 Results and discussion

All three CAST detectors were collecting data during 2003 and 2004, the sun tracking data being collected for 300 hours and the background data for an

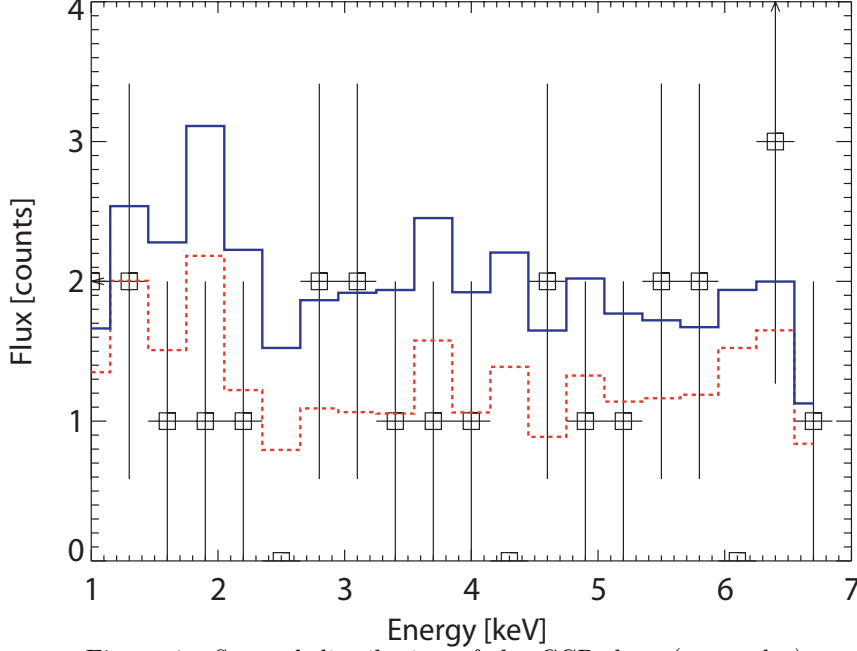


Figure 1: *Spectral distribution of the CCD data (rectangles), expectation for the best fit  $g_{a\gamma}$  (dashed line) and expectation for the 95% CL limit on  $g_{a\gamma}$  (continuous line), in units of counts per energy bin in the spot area ( $9.35 \text{ mm}^2$ ).*

order of magnitude more time. All three detectors were significantly improved from 2003 to 2004. In the system x-ray telescope — CCD detector, the pointing stability of the x-ray telescope was continuously monitored and allowed to reduce the area of the detector where the axion signal was expected, by a factor of 5.8. This was an essential improvement for the signal to noise ratio, since the same expected signal was concentrated in a much smaller area. The integrated background in the spot area, which is now smaller, is consequently reduced by the factor of 5.8 mentioned above. Moreover, with better shielding, the specific background level dropped by another factor of 1.5. Detailed information on the specifics of the x-ray telescope and the CCD detector can be found in references 27,28 and 29. The data set, shown in fig 1 collected during 2004 allowed us to derive a lower upper limit on the axion-photon coupling. The analysis procedure is thoroughly described in reference 24. The result for axion-photon coupling  $g_{a\gamma}$  is an upper limit of  $8.9 \cdot 10^{-11} \text{ GeV}^{-1}$ , at the 95% CL.

The TPC detector, looking for sunset axions, was housed in a new shield-

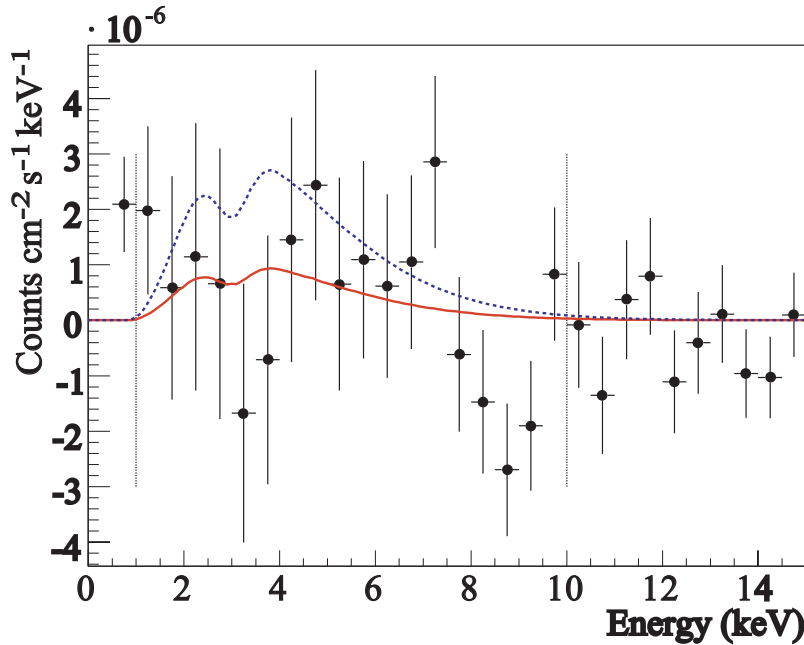


Figure 2: *Experimental subtracted spectrum (bullets), expectation for the best fit  $g_{a\gamma}$  (continuous line) and expectation for the 95% CL limit on  $g_{a\gamma}$  (dashed line), for the TPC data.*

ing, consisting of a 5 mm thick copper box which was inside successive shielding layers of 22 cm of polypropylene, 1 mm of Cadmium and 2.5 cm of Lead. Care has been taken so that all these materials were of low radioactivity. Permanent flushing with nitrogen was creating an overpressure, pushing away any radon contamination in the area of the detector. The background level was succeeded to be reduced by a factor of 4.3. Detailed information on the TPC detector can be found in references 24 and 25. The results are shown in figure 2. The upper limit on  $g_{a\gamma}$  from the TPC data for 2004, is  $1.29 \cdot 10^{-10} \text{ GeV}^{-1}$ , at the 95% CL.

The Micromegas detector was placed on the west end of the magnet, looking for sunrise axions. The newly designed version of the detector operated smoothly during 2004 data taking and the analysis technique has been also improved, resulting in a background level, suppressed by a factor of 2.5 compared to the 2003 data set <sup>26, 24</sup>). These improvements allowed to set an upper limit to  $g_{a\gamma}$  from the MM 2004 data of  $1.27 \cdot 10^{-10} \text{ GeV}^{-1}$ , at the 95%

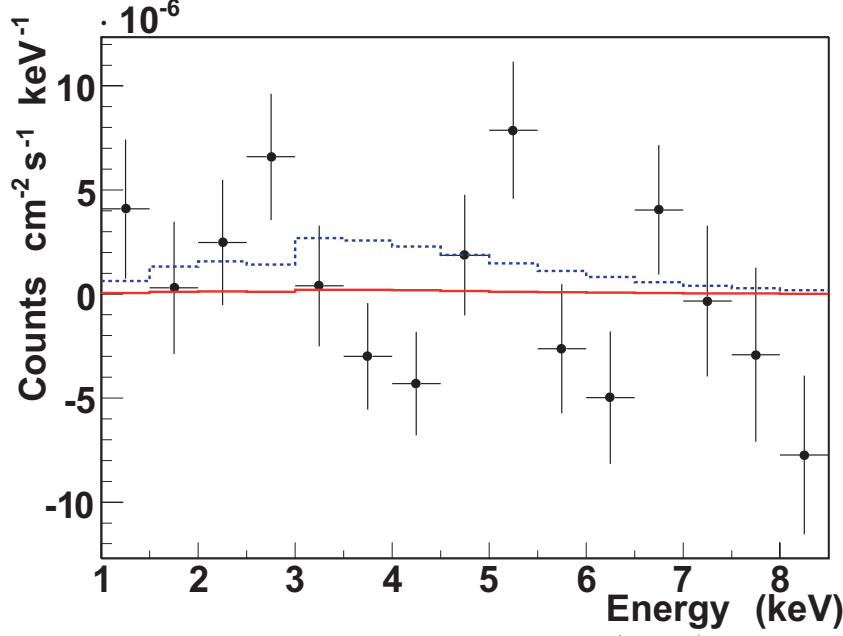


Figure 3: *Experimental subtracted spectrum (bullets), expectation for the best fit  $g_{a\gamma}$  (continuous line) and expectation for the 95% CL limit on  $g_{a\gamma}$  (dashed line), for the Micromegas data.*

CL. Taking into account all three detectors and the data sets of both years 2003 and 2004, for axion masses below 0.02 eV, we obtained a final upper limit of

$$g_{a\gamma} < 8.8 \cdot 10^{-11} \text{GeV}^{-1} \text{ (95\% CL)}$$

For higher axion masses the axion photon-coherence is lost since their oscillation length is reduced. The exclusion plot in figure 4 shows the CAST result together with results from previous experiments, as well as limits derived from astrophysical and cosmological arguments. For the first time an experimentally set limit is better than the one given from arguments based on the population of Horizontal Branch stars in globular clusters <sup>24</sup>).

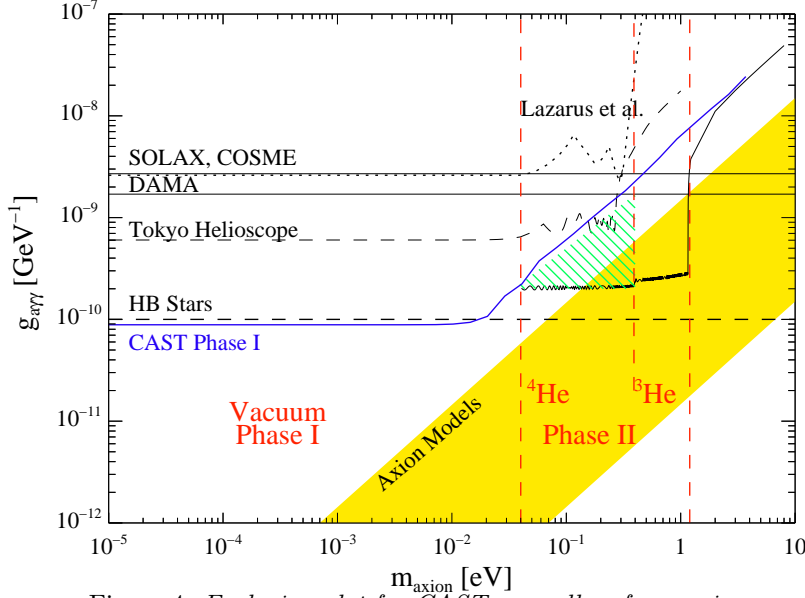


Figure 4: *Exclusion plot for CAST, as well as for previous experiments. Limits from astrophysical and cosmological arguments are also shown. The corridor of axion models below 1 eV is checked for the first time.*

## 5 Prospects - CAST phase II

For low axion masses, the axion - photon oscillation length exceeds by far the length of the magnet, that is axions and virtual photons are travelling coherently and the axion - photon transformation probability depends on  $B^2 L^2$ . In this low axion mass region, recoil effects in the Primakoff effect (and its inverse effect) may be neglected and the energies of both particles are considered to be the same. However, at higher axion masses, the axion - photon coherence is lost due to the axion mass which prevents it from travelling in phase with virtual photons in the transverse magnetic field. In order to restore the coherence condition, we fill the magnet channels with gas, so that the photon acquires an effective mass  $m_\gamma > 0$ . The momentum transfer becomes

$$q = \frac{m_a^2 - m_\gamma^2}{2E} \quad (5)$$

as opposed to



$$q = \frac{m_a^2}{2E} \quad (6)$$

The conversion probability in gas is given by

$$P_{a \rightarrow \gamma} = \left[ \frac{B g_{a\gamma\gamma}}{2} \right]^2 \frac{1}{q^2 + \Gamma^2/4} \left[ 1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos(qL) \right] \quad (7)$$

where  $L$  is magnet length and  $\Gamma$  is the absorption coefficient, which is zero in vacuum. The effective photon mass is given by

$$m_\gamma \approx \sqrt{\frac{4\pi a N_e}{m_e}} = 28.9 \sqrt{\frac{Z}{A}} \rho \text{ eV} \quad (8)$$

and the coherence condition is

$$qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}} \quad (9)$$

The above condition is restored only for a narrow mass range around  $m_\gamma$ , which for helium-4 can be adjusted by changing the gas pressure as follows:

$$m_\gamma \text{ (eV)} \approx \sqrt{0.02 \frac{P(\text{mbar})}{T(K)}} \quad (10)$$

As a matter of fact, every specific pressure allows to test a specific axion mass. It is evident that, the higher the pressure, the higher the photon effective mass, the higher the axion mass under test. The transformation probability is shown in figure 5 for two pressures, namely 6.08 and 6.25 mbar, indicating that the step has to be well below this difference (0.17 mbar) in order to cover fully the axion mass range. In our measurement program we used half this difference as step, namely 0.083 mbar. It is evident that for every step, there is a new discovery potential.

Measurements with helium-4 have been already carried out up to a pressure of 13.43 mbar, with small pressure steps. This is the upper limit in pressure, before condensation effects take place. This search tested the axion mass region up to 0.39 eV. The area explored with helium-4 is designated in figure 4. Analysis is going on for these data and results will be published in a forthcoming paper. CAST is currently upgraded in order to use helium-3 as a buffer gas, allowing to increase the pressure up to about 135 mbar and extending its sensitivity up to 1 eV axions. The above CAST searches will allow to explore experimentally the area of masses and coupling constants predicted by the axion models, as it is shown in figure 4. For higher pressures there is a limitation coming not only from condensation effects, but also from the photon absorption coefficient which increases with pressure.

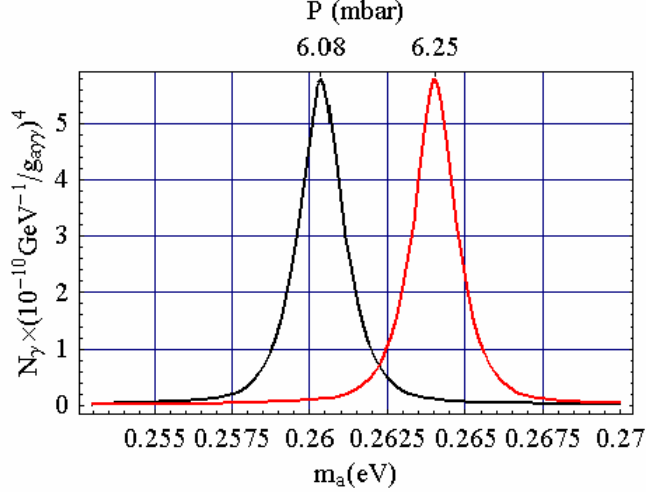


Figure 5: *Probability of axion to photon conversion for two pressures. The step we used was about half this difference in order to scan fully the range of axion masses.*

## 6 Conclusions

CAST searched for photons arising from axion conversion in a LHC test magnet of 9.26 m length and 9 T magnetic field, for axion masses less than 0.02 eV. Axions are expected to be produced in the sun by the Primakoff process. The experiment obtained the best experimental limit so far (an order of magnitude better than previous experiments). Our result is for the first time better than limits set by astrophysical arguments related to the population of Horizontal Branch stars in globular clusters. This population depends on their helium-burning lifetime. We have searched for higher mass axions, up to 0.39 eV, by filling the magnet bores with helium-4 buffer gas. Under these conditions, photons acquire a small mass depending on pressure and coherence condition between axions and photons is restored. Results from this search will be published in a forthcoming paper. CAST is now under upgrade, in order to fill the magnet bores with helium-3, allowing us to explore axion masses up to 1 eV and testing the range of  $g_{a\gamma} - m_a$  values anticipated from QCD axion models and also the possible existence of large extra dimensions<sup>31)</sup>. Axions of this range of masses could be candidates for a hot dark matter component of the universe<sup>32)</sup>.

## 7 Acknowledgments

I would like to thank K.Zioutas, A.Liolios, I.Savvidis and T.Papaevangelou for fruitful discussions. I would like also to thank E. Ferrer Ribas and M.Kuster for suggestions/comments. We acknowledge support from NSERC (Canada), MSES (Croatia), CEA (France), BMBF (Germany) under the grant numbers 05 CC2EEA/9 and 05 CC1RD1/0, the Virtuelles Institut für Dunkle Materie und Neutrinos – VIDMAN (Germany), GSRT (Greece), RFFR (Russia), CICyT (Spain), NSF (USA) and the helpful discussions within the network on direct dark matter detection of the ILIAS integrating activity (Contract number: RII3-CT-2003-506222). We thank CERN for hosting the experiment and for the contributions of CERN staff.

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